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Prospect of concentrating solar power in China—the sustainable future

Qu Hang[a,*], Zhao Jun[a], Yu Xiao[b], Cui Junkui[a]

[a]*School of Mechanical Engineering, Tianjin University, Tianjin 300072, China*
[b]*School of Civil Engineering, Ludong University, Yantai 264025, China*

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Abstract

Limited fossil resources and severe environmental problems require new sustainable electricity generation options, which utilize renewable energies and are economical in the meantime. Concentrating solar power (CSP) generation is a proven renewable energy technology and has the potential to become cost-effective in the future, for it produces electricity from the solar radiation. In China, the electricity demand is rapidly increasing, while the solar resources and large wasteland areas are widely available in the western and northern part of China. To change the energy-intensive and environment-burdensome economical development way, Chinese government supports the development of this technology strongly. These factors altogether make China a suitable country for utilizing CSP technology. In this paper, the potential of CSP in China was studied and strategies to promote development of this technology were given.

Keywords: Renewable energy; Potential; Concentrating solar power; China

Contents

*Corresponding author. Tel./fax: +86 22 27407617.
E-mail address: quhang0922@yahoo.com.cn (Q. Hang).

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1. Introduction

With a population of more than 1.3 billion people, China has still a relatively low per capita energy consumption compared to the industrialized countries. This value is 1299 kg of coal equivalent (kgce) in 2003, which represents only 11.5% and 22.9% of that of the United States of America and Japan, respectively [1]. However, the primary energy consumption in China had been increasing at an annual growth rate of 8.4% between 1990 and 2004, which is much higher than that of any industrialized country [2].

During the period of 1990–2004, electricity generation had grown at an annual average of 9.7%, while installed capacity had increased more than three-fold, from 138 to 442 GW. Since the year of 2002, due to rapid expansion of energy-intensive industry sector and the kept increasing residential electricity demand, the growing electricity demand surpasses the power generation capacity, and lead to a demand-supply gap, so China had to build many power plants, and the annual electricity demand growth averaged 14.6% from 2002 to 2005. This trend is expected to exist further in the near and mid term, otherwise China could face serious economic consequences [2].

Coal is the largest primary energy resource in China, and the reserves of oil and gas are relatively small. Due to the dominant use of coal for electricity generation, which represents 75.9% in total in 2005 [3], serious environmental negatives are caused. Air pollution in big cities, caused partly by coal-fired power plants, are creating severe health problem to the inhabitants; coal mining has led to many environmental problems, such as ground sedimentation, land degradation and water contamination. These local negatives are further accompanied by the increasing emissions of the greenhouse gas of CO_2, which contributes the most to the global climate change.

Climate change has called great attention worldwide, and it is the first issue in the World Economic Forum Annual Meeting of 2007 at Davos [4]. China accounted for 44% of the growth in global CO_2 emissions over the period of 1990–2004. Recent analysis of IEA suggests that China could surpass the US to become the world's largest source in CO_2 emissions by 2009, rather than 2020 as previously forecasted [2]. The necessity of a gradual change of the current coal-dominated energy construction seems to be inevitable, otherwise China will face more and more pressure from the international society.

As part of the solutions for the above-mentioned negative effects, China is looking for environment friendly renewable energy sources. As indigenous resources, the renewable

energy has additional positive effects of promoting local economy development, mitigating financial burden from energy imports, and improving energy safety of the country.

Concentrating solar power (CSP) is a promising option, and this technology represents a sustainable energy source with huge potential for China.

2. Energy situation in China

China's economy continues to rapidly expand. The official economic growth objective of quadrupling 2000 GDP by 2020 is relatively moderate, with annual rate of about 6.6% from 2005 to 2020 [2]. To meet this rising electricity demand, China would have to install as much as 635–860 GW of additional generation capacity by 2020, an amount comparable to EU's total installed capacity in 2003 (Table 1) [2]. That means, under these assumptions, 59–66% of China's 2020 generating capacity remains to be built. However, as mentioned above, recent trends in energy demand growth and resource use far exceed this pace, this indicates one of the highest growth rates worldwide and one of the biggest challenges for the Chinese economy.

It is obvious that most of the Chinese electricity generating capacity is based on thermal power plants, and coal is by far the most important fuel for power generation (Table 2).

In the coming years, China is expected to continue to depend mainly on coal as an energy source in the power sector. But the importance of gas will increase in the future, and wind and nuclear power generation will probably play important roles in the Chinese power sector.

It has raised a lot of concern in China that the power sector is strongly dependent on the fossil fuel of coal and, in the future, the gas. In China, the only in large quantities

Table 1
Forecast of electricity generation until 2020 [2]

Forecast	2005–2020
Annual growth rate of GDP	6.6%
Total electricity demand (TW h)	5337–6432
Capacity to install (GW)	635–860

Table 2
Chinese power sources in 2004 and forecast [5,6]

Power sources	2004 Capacity (GW)	2020 Target capacity (GW)	Implied average annual growth (%)	Estimated resources
Coal	305	563	3.9	1,042,100 Mtoe
Natural gas	0.7	60	32	2.35 trillion m^3
Wind	0.8	30	25	Land: 235 GW Offshore: 750 GW
Hydro	108.3	300	6.8	Total: 541 GW Small: 125 GW
Solar (PV)	0.06	1.8	125	3.96 kW h/(m^2 day)
Nuclear	6.84	40	11.7	n/a
Biomass	2	30	18.4	n/a

available fossil resource is coal throughout this century. However, as already mentioned above, the use of coal as the primary energy source causes numerous environmental problems. The air quality of Chinese cities is amongst the worst in the world, in part because of the use of coal for power generation. At the same time, the combustion of coal, like other fossil fuels, increases the CO_2 emissions contributing to the greenhouse effect and consequent climate changes, will affect China much more than the industrialized countries.

As one of the energy sources, the increasing use of natural gas can reduce some negative environmental effects, but it will also contribute to climate changes through increased CO_2-emissions. In addition, China will depend largely on gas imports in the future, as the Chinese per capita natural gas reserve is only 5% of that of the world [7]. Thus, a large part of China's export earnings will have to be paid for the imports and the economy might have to be suffered from energy price changes on the world market. The only way to reduce the import dependency, and the environmental problems caused by combustion of fossil fuels, is to use indigenous renewable energy sources that are sufficiently available in China. Currently only hydro-power contributes significantly to the power generation in China. Except for the hydro-power plants which contribute 24.5% of the whole power generation in 2004, only very little (2860 MW) of the grid capacity is based on renewable energies. Generally biomass power plants account for the largest part of the non-hydro renewable electricity generation capacity. The wind energy has experienced a tremendous growth since mid of 1980s, from the installed capacity of 40 MW in 1991 to the capacity of around 800 MW by 2004. Wind power has a large potential in the coming years, and the potential of other renewable energies is also significant [6].

3. CSP systems

In this section, a description and assessment of the CSP systems is given, which incorporate three different design alternatives: parabolic trough, power tower and dish/stirling. These systems are solar thermal concentrating devices: direct normal insolation (DNI) is reflected and concentrated onto a receiver/absorber where it is converted to heat, then the heat is used to produce steam to drive a traditional Rankine power cycle [8]. Table 3 lists the performance data for various CSP technologies [9].

The function principle and the main system parameters of these power plants are described below.

Table 3
Performance data for various concentrating solar power technologies [9]

CSP systems	Capacity range (MW)	Concentration	Demonstrated annual solar efficiency (%)	Thermal cycle efficiency (%)	Land use $m^2/(MW\,h\,a)$
Parabolic trough	10–200	70–80	10–15	30–40	6–8
Power tower	10–150	30–1000	8–10	30–40	8–12
Dish-stirling	0.01–0.4	1000–3000	16–18	30–40	8–12

3.1. Parabolic trough system

Parabolic trough system is line-focusing, and it uses the mirrored surface of a linear parabolic concentrator to focus direct solar radiation to an absorber pipe running along the focal line of the parabola. The heat transfer fluid (HTF) or water (in case of direct steam generation, DSG) inside the absorber pipe is heated and pumped to the steam generator, which in turn is connected to a steam turbine to produce electricity. Normally a natural gas burner is used to produce steam at the time of insufficient radiation [10].

Parabolic trough technology has demonstrated its ability to operate in a commercialized environment by the nine solar power plants in California, the United States, which developed by Luz International Limited between 1984 and 1990. The accumulated 154 years' operation experiences of these plants indicate the low technical and financial risk in developing near-term plants [11].

During the long term's operation of the plants in California, electricity generation has been improved significantly by improving operation and maintenance procedures. The Kramer Junction, one of the three sites locating the nine plants, has achieved a 30% reduction in operation and maintenance costs during the last 5 years [12]. Besides many detailed modifications, several major improvement works have been proceeding on, including DSG and Integrated Solar Combined Cycle System (ISCCS). Using direct solar steam generation, the HTF/water heat exchanger will no longer be required. Thus, by reducing investment costs and at the same time increasing system efficiency, a significant reduction of electricity generation cost is expected; ISCCS is a new design concept that integrates a parabolic trough plant with a gas turbine combined-cycle plant. The ISCCS has called much attention because it offers an innovative way to reduce cost and improve the overall solar-to-electric efficiency [13].

3.2. Power tower system

Power tower system is characterized by the centrally located large tower. A field of two-axis tracking mirrors (heliostats) reflects the solar radiation onto a receiver that is mounted on the top of the tower, where the solar energy is absorbed by a working fluid, then used to generate steam to power a conventional turbine. To maintain constant steam parameters at fluctuant solar irradiation or even at the time of no shining, the system can be integrated with a fossil back-up burner or a thermal storage unit [14].

3.3. Dish/stirling system

Dish/stirling system uses a parabolic dish concentrator to focus direct solar radiation to a thermal receiver, and a heat engine/generator unit located at the focus of the dish generates power. Typically, a stirling engine is used; other designs use gas (Brayton) turbines. A hybrid operation using natural gas is also possible [14].

3.4. Comparison of the systems

With capacity of 10–400 kW, the dish/stirling is rather small. It does not enjoy the same economy of scale as the other two systems, so it is doubtful whether dish/stirling will ever

form the backbone of multi-GW grid connected systems. However, this system could play an important role in the decentralized part of the solar economy.

Parabolic trough and power tower are both centralized systems, and they are candidates for applications with grid connection. The tower is still immature and the large scale utilization of parabolic trough could be realized in near and mid-term [15].

4. Potential of CSP in China

This section will focus on the siting parameters of centralized CSP systems, to investigate the potential of such plants in China. There are many technical and economical issues related to siting of the CSP plants, the main factors are listed in Table 4 and studied, respectively.

4.1. Assessment of solar energy resources

China is a large country with a land area of about 9.6 million km^2, and it belongs to those so-called sun belt countries. Fig. 1 shows the Chinese map of DNI [17]. Generally speaking, the solar resource is abundant in China, but greatly diverse in various areas. The direct normal solar radiation ranges from less than $2\,kW\,h/(m^2\,day)$ in part of the south-east to more than $9\,kW\,h/(m^2\,day)$ in part of the west.

CSP systems require high DNI for cost-effective operation. Sites with excellent solar radiation can offer more attractive levelized electricity prices, and this single factor normally has the most significant impact on solar system costs [16].

It is generally assumed that CSP systems are economical only for locations with DNI above $1800\,kW\,h/\,(m^2\,a)$ (circa $5\,kW\,h/\,(m^2\,day)$) [9]. As can be seen from Fig. 1, most of the northern and the western parts of China's land area can satisfy this requirement. Tibet has the best DNI resource in China, and part of Inner Mongolia, Sinkiang, Qinghai and Gansu also possess of DNI resource of more than the a.m. limit.

4.2. Assessment of the land use and land cover

Except for the solar radiation, CSP plants require a large area for their solar field, approximately a land area of $20{,}234\,m^2$ is required per megawatt of electricity produced in a solar thermal power plant [9]. As China is a very intensively populated country, the agricultural land and forest, which is needed for crop and biomass production for the

Table 4
Main siting factors of concentrating solar power plant [16]

Siting factor	Requirement
Solar resource	Abundant, $>1800\,kW\,h/\,(m^2\,a)$ for economical operation
Land use	5 acres ($20{,}234\,m^2$) per megawatt of electricity production
Land cover	Low diversity of biological species, limited agriculture value
Site topography	Flat, slope up to 3%, 1% most economical
Infrastructure	Proximity to transmission-line corridor, natural gas pipeline and rail transportation system
Water availability	Adequate supply, otherwise dry cooling

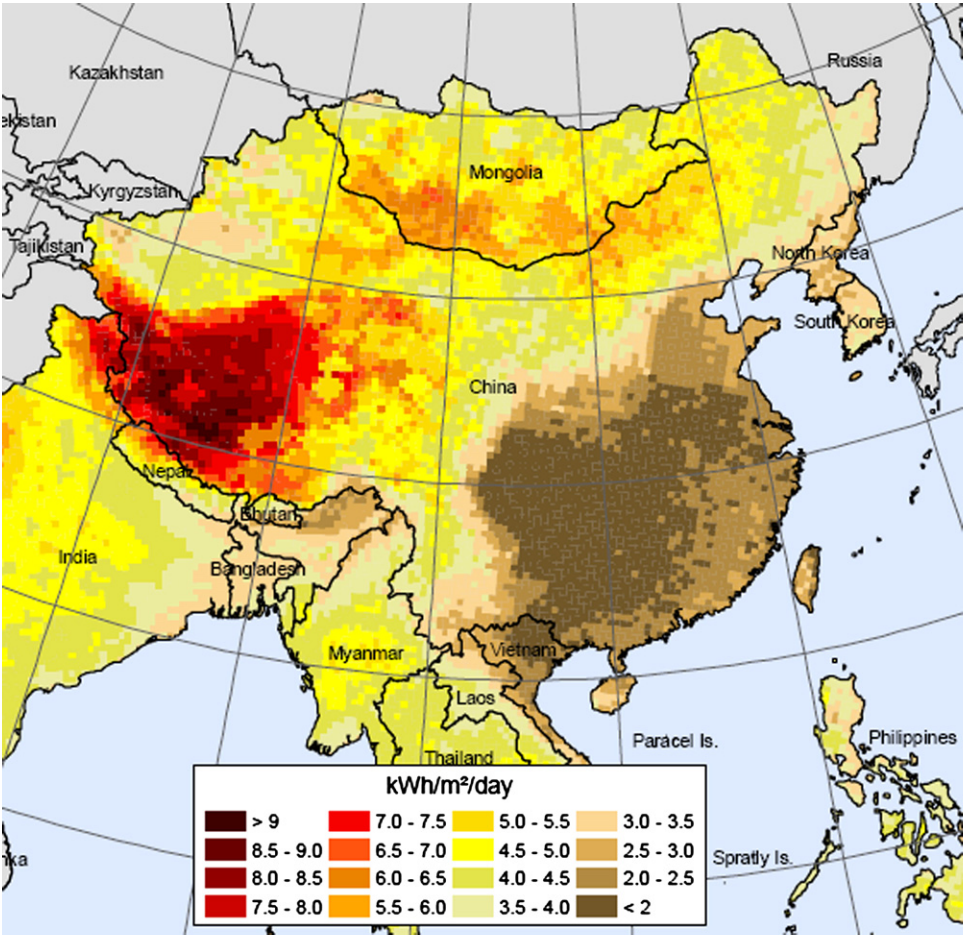

Fig. 1. Chinese map of direct normal solar radiation (Source: NREL).

growing population, should not be considered for siting power plants. Thus, only wasteland, which is unsuitable for agricultural and residential use, can be considered as construction sites.

It is estimated that China has 2.63 million km^2 of such wasteland. Most of the wasteland is located in the northern and the western China where the solar radiation is among the highest (Fig. 1). Tibet, Inner Mongolia and Qinghai, with wasteland of 987,900 km^2 [18], and annual normal direct solar radiation more than 1800 kW h/m^2 in most of the areas, seem to be especially suitable locations.

Assuming just 1% of the whole wasteland is taken as potential site for solar thermal power plants, an area of 26,300 km^2 still remains. This indicates that the land availability will not become barrier in the future. Even if only power tower, the technology with the higher land area requirement, were used, 1300 GW of electricity generation capacity could be installed, about 2 times of the forecast of the capacity to be installed until 2020 (Table 1).

4.3. Other factors

Except for solar energy resources, land use and land cover, the other siting factors are not much different compared with those of the traditional steam power plant. Land slope is an important characteristic during the siting investigation of a CSP plant. An overall slope of less than 1% is preferable; higher slope up to 3% is also acceptable, but will elevate the cost. For comparison, a thermal fired plant requires a land slope of 1–3% [16,19]. Another siting issue is the water availability. The water used at a Rankine steam CSP plant is for the steam cycle, mirror washing, and mostly the cooling tower. If sufficient water is not available at the site, dry cooling system is the other choice. However, the plant electricity cost can be raised by 10% in this case.

Access to transmission line and natural gas pipeline are also important factors for selecting the sites. Transmission line costs can be very high, so proximity of potential CSP plant to the grid is very important. With fossil fuel, preferably natural gas, as supplement for the solar energy resource, the solar thermal power plants have the capacity to provide firm power in a hybrid configuration. However, the last issue is significant, but not determinant [16].

A feasibility study involving all these factors must be implemented before the location is determined for a CSP plant.

5. Policies and strategies

China's energy policy target is to reach a 15.4% renewable energy share by the year of 2020, and 27.5% in 2050, respectively [20]. The instruments to reach this goal range from the 'Law of the People's Republic of China on Renewable Energies' to the political and financial support of research and development of renewable energy sources [21]. The Ministry of Science and Technology of the People's Republic of China has listed CSP as an important research issue in the 'Summary of National mid & long-Term Science and Technology Development Plan' (2006–2020) [22].

Up to now, no commercial solar thermal power plant is in operation in China. Only a demonstration power tower of 75 kW was built in Nanjing, Jiangsu Province in 2005.

Technology and cost are two major barriers to the CSP development in China. To resolve the critical technological problems, the Ministry of Science and Technology of the People's Republic of China, with RMB100 million (USD 12.9 million) from central governmental budget, is funding CSP research in order to resolve the critical problems and bring CSP into the position to successfully enter the market [22]. Also China has been active in many international research and development activities, to accelerate this process.

Using current CSP technology, the electricity generation cost of 10–12 US cents/kW h is still higher than that of traditional thermal-fired plant [9]. However, further significant cost reduction can be expected for this still young technology. Also, the Chinese government has carried out regulation on renewable power pricing to make solar power profitable [23]. Moreover, this 'zero-emission' technology offers tremendous environmental positives concerning CO_2 and other emissions. Despite all these advantages, CSP is still a very cost-intensive technology, which prohibits its use in developing countries up to now. Thus, low capital costs are a precondition for the economic operation of this technology. Taking all these factors into consideration, it becomes obvious that CSP offers a cost-effective opportunity for international cooperation against climate change. In the context of Clean

Development Mechanism (CDM), formulated in the Kyoto Protocol, CSP technology can offer interesting investment opportunities for the industrialized countries, to provide the necessary capital to the developing countries. This would help to protect the highlighted climate change by reducing CO_2 and other greenhouse emissions, and in the meantime support the sustainable development of the developing countries with rapidly increasing electricity demand, including China.

6. Conclusions

Against the background of an increasing energy demand and growing environmental problems in China due to the use of fossil fuels, CSP technologies offer interesting opportunities for China. These technologies can easily be adapted to the northern and western part of China due to the abundant solar radiation and the large wasteland.

Based on the total electricity production in 2004 and forecast for the year of 2020 (Table 2), the CSP was not taken into account, this indicates that we have only taken initial steps in the process of utilizing this technology in comparison with other renewable power sources and that much more efforts would be necessary. To bring it to a market-ready position, the government's support and strategies are necessary.

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